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RESEARCH ON THE THERMICON IMAGE TUBE (U)

FINAL REPORT

PREPARED BY
C. F. EVE

JULY 1970

U.S. ARMY MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT CENTER

R&D PROCUREMENT OFFICE

FORT BELVOIR, VA. 22060

CONTRACT DA-44-009-AMC-438(T)

WESTINGHOUSE RESEARCH LABORATORIES

PITTSBURGH, PENNSYLVANIA 15235

July 27, 1970

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FINAL REPORT

January 10, 1964 through June 9, 1970

U.S. ARMY MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT CENTER

R&D PROCUREMENT OFFICE

FORT BELVOIR, VA. 22060

Contract: DA-44-009-AMC-438(T)

Contractor: Westinghouse Research Laboratories
                                   Pittsburgh, Pa. 15235

Date of Contract: January 10, 1964

Work performed by   W. C. Divens, C. F. Eve, P. H. Foreman,
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Report Prepared by: C. F. Eve

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Group 4

DOWNGRADED AT 3 YEAR
INTERVALS – DECLASSIFIED
AFTER 12 YEARS
DOD DIR 5200.10

ABSTRACT

(U)   The report describes work on the development, design, construction and testing of the cooled Thermicon system, an infrared television system for night vision. Principles of operation and theoretical predictions of performance are given. The design and fabrication of sealed tubes and the problems of sensing layer preparation are described. A complete system, including optics, camera and cooling was built. A novel scheme for the enhancement of contrast by background subtraction was successfully implemented in a unit called a video correlator. The performance of the entire system was evaluated in outdoor night-time field tests at Ft. Belvoir, and also in a number of laboratory measurements. Two uncooled Thermicon tubes were also made and tested.

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CONTENTS

Contract DA-44-009-AMC-438(T)

1. Introduction

(U)   The present contract is a continuation of a program conducted
at the Westinghouse Research Laboratories and supported by the U.S. Army,
ERDL and NVL, Ft. Belvoir, since April 1958 under consecutive contracts
DA-44-009-ENG-3490, DA-44-009-ENG-4427, DA-44-009-ENG-4887 and, from
January 1964 to the present, DA-44-009-AMC-438(T). The overall objective
of the program has been the development of an infrared television system
that will permit the passive night-time imaging of objects in a terrestial
scene by virtue of the small temperature differences existing between
these objects and the scene background.

(U)   The Westinghouse approach to this objective is based on an infra-
red television camera tube called the Thermicon. By the beginning of the
present contract an uncooled version of this tube had been developed and
a number of sealed tubes fabricated. In addition a cooled version in the
form of a laboratory demountable tube had been demonstrated. This cooled
tube showed some, though not all, of the additional sensitivity expected
on theoretical grounds to result from the cooling.

(U)   The objectives of the present contract were to realize the full
theoretical sensitivity of the cooled tube, to design, develop and fabri-
cate sealed cooled tubes, and to design and build a complete transportable
Thermicon system suitable for demonstrating and testing the performance
of the Thermicon in the field. All of these objectives have now been
achieved.

2. Principles of Operation

2.1 General

(U)   The Thermicon consists essentially of a vidicon in which the
normal photoconductive sensing layer is replaced by a thin bolometric
(temperature sensitive) film. Infrared radiation is focussed onto this
film to produce there a temperature distribution corresponding to that in
the viewed scene. This temperature distribution is converted by the

temperature coefficient of resistance of the film into a corresponding distribution of electrical resistance, which is read out by a scanning beam of low velocity electrons as in a vidicon to produce a video signal.

(U) Several advantages stem from the use of a bolometric sensing layer in place of a photoconductive one. The first results from the exponential dependence of bolometer resistance on temperature, which produces a superlinear variation of current with infrared signal. This in turn provides an enhancement of contrast that is sorely needed for the imaging of typical terrestrial scenes, in which the variations of temperature are only a few degrees about an average temperature of some 300°K. In the photoconductive sensing layer of a true infrared vidicon, the response is sublinear because the gamma of the photoconductor is always less than unity. This degrades rather than enhances signal contrast. The second advantage of a bolometric sensing layer over a photoconductor is that the response of the former is not dependent on the wavelength of the infrared radiation. It is thus relatively easy to tailor the spectral response of the tube to any desired form by use of suitable optical filtering elements. In the present application, the tube operates primarily in the 8-13 micron region of the spectrum, where most of the radiated energy from terrestrial objects is located. A third advantage of the bolometric tube is that it can be designed to operate without any cooling, albeit at the price of a loss in signal contrast. In some applications this loss may be an acceptable price to pay for the great practical advantage of uncooled operation. This option is not available with a photoconductive camera tube having a spectral response suitable for imaging terrestrial scenery.

2.2 Structure of Sensing Layer

(U) The sensing layer, or retina, of the Thermicon tube is in fact a 3-layered structure. It is depicted in the inset of Fig. 1. Mechanical support is provided by a thin nitrocellulose film, prepared from a nitrocellulose lacquer, mounted on a metal ring. Onto the surface of the nitrocellulose film is deposited a layer of gold black. This layer serves two functions. First, it acts as an absorber of the incident

infrared radiation. This is necessary since the bolometer, which is a
high band gap intrinsic semiconductor in order to provide a high tempera-
ture coefficient of resistance, is transparent to all but the very short
wavelength infrared radiation. The second function of the gold black
layer is as an electrode or backplate for the extraction of the video
signal from the back surface of the bolometer. Finally, a layer of semi-
conducting material is deposited over the gold black to form the bolometer.
The infrared radiation is incident on the nitrocellulose side of the
retina, passes through the support film and is absorbed in the gold black,
where it produces a temperature distribution. This temperature distribu-
tion is transferred to the semiconducting bolometer by thermal conduction.
The bolometer transforms the temperature distribution into a distribution
of electrical resistance that is read out by an electron beam scanning
the free surface of the bolometer. The resulting video signal current is
fed to the load resistor of a video amplifier _via_ a wire connected to the
gold black layer of the retina.

(C)   The spatial resolution attainable is limited by lateral heat
conduction in the layers of the retina, which tends to smear out the finer
details of the temperature distribution. In the support layer, this
effect is minimized by choice of a material with low thermal conductivity
(nitrocellulose) and use of the minimum thickness consistent with adequate
mechanical strength. This thickness turns out to be approximately 200
angstroms. In the gold black layer the requirement of low thermal con-
ductance conflicts with the requirement of adequate infrared absorption.
Both of these effects are intimately connected with the electrical con-
ductance of the layer. The conduction electrons give rise to the thermal
as well as the electrical conductance of the layer, the two quantities
occurring in a fixed ratio expressed by the well-known Wiedemann-Franz law.
At the same time the conduction electrons are also responsible for the
infrared absorption through the mechanism of free carrier absorption.
Thus both the thermal conductance and the infrared absorption are fixed by
the electrical conductance. In practice an infrared absorption of no less
than about 70% is required, otherwise the response time becomes unacceptably

large. This fixes a minimum value of thermal conductance that can be attained. Fortunately, the value thus arrived at represents a tolerable compromise. In fact it makes the thermal conductance of the gold black layer comparable to that present in the 200 Å thick nitrocellulose layer.

(C)   The lateral thermal conductance of the semiconducting bolometric layer cannot be minimized by making this layer very thin since this would make the electrical capacitance of the layer much too great for the proper functioning of the readout beam. Once during each frame of the scan cycle the beam has to charge the exposed surface of the layer down to cathode potential, while the other surface is held at the voltage applied to the gold black electrode. This applied voltage must be at least a few volts in order to be large compared with the apparent energy distribution in the electron beam. The amount of beam current required for this periodic charging then is determined by the capacitance of the layer. Conversely, the maximum capacitance that can be tolerated is determined by the available beam current. In practice beam currents of about 10^{-7} A are available from vidicon type guns. For an applied voltage of 10 volts and a frame rate of 1/30 second, this requires a capacitance no greater than 330 pF. For a raster area of 3.5 cm^2 and unit dielectric constant this implies a minimum layer thickness of 10 microns. This is 500 times the thickness of the nitrocellulose support layer. The lateral thermal conductance in so thick a layer would normally be prohibitively great for the present application. This problem is solved by deposition of the bolometric material in a very porous, low density form. This is achieved by evaporation of the material in an inert atmosphere at a suitably chosen pressure. The resulting layer is referred to as a smoke layer, a name derived from the appearance of the material during the evaporation. The macroscopic density of the smoke layer is only about 1% of the density of the bulk material and its thermal conductivity is extremely small. Observations show that the spatial resolution of the retina is independent of the thickness of the bolometric layer. We conclude that this layer makes a negligible contribution to the overall lateral heat spread in the retina. Observations on retinas with different thicknesses of gold black and

nitrocellulose layers indicate that these two layers make comparable contributions to the heat spread.

2.3 Frame Storage

(C)   In addition to the requirements of a high temperature coefficient of resistance and a very low thermal conductivity, there is an important constraint on the electrical resistivity of the bolometric material. This constraint derives from the requirement of frame storage in the sensing layer. By frame storage is meant the ability of an element of the sensing layer to deliver on each successive scan a video signal impulse proportional to the total infrared energy incident on the element during the entire interval between successive scans. The element then, in effect, integrates or stores the signal for a frame period. Such frame storage not only enhances the signal to noise ratio as a result of the integration but also provides a 100% continuous duty cycle for each element of the sensing layer. Thus, for example, a pulsed point source of radiation, such as a gun flash, will be detected even though the pulse is incident on the element of the sensing layer at an instant when it is not being addressed by the scanning beam. This highly desirable property is not possessed by conventional mechanically scanned detector systems.

(U)   Frame storage or integration is achieved by proper choice of the RC time constant or dielectric relaxation time of the bolometric layer. When the beam impinges on the surface of an element, electrons land on the surface until its potential is reduced to that of the cathode. Further landing of electrons is then energetically impossible. Thus at the instant the beam moves away from the element, the free surface is at cathode potential while the opposite surface is at the fixed potential, V_T, applied to the gold black. Thus a potential difference initially equal to V_T appears across the element. This potential difference decays during the interval between two successive scans. By the time the beam returns to the element for the next scan the free surface potential has risen from zero (cathode potential) to some value, V, between zero and V_T. On this second scan the beam deposits onto the surface sufficient charge to reduce the potential from V back to zero, i,e. to replace the charge that leaked away during

the frame period. This quantity of charge constitutes the video signal impulse from that element. Its magnitude depends on the value V to which the surface potential went during the frame interval between scans. This in turn depends on the RC time constant of the element, R being the resistance and C the capacitance between opposite surfaces of the element. RC is dependent on the absorbed infrared radiation through the temperature dependence of R. The charge lost from the surface by conduction through R during a frame period is simply the time integral of the instantaneous current through R. Thus the charge deposited at the end of each frame period represents this integrated signal. However, if the average value of R is such as to make RC small compared with the frame period then the capacitance C will completely discharge during the period and the video current will saturate, being dependent only on C and V_T, and not on R. Thus for frame storage operation RC must not be less than the frame period. If RC is large compared with the frame period frame storage still occurs, but the loss of charge per frame, and hence the video current, becomes very small. For optimum frame storage operation, RC should be approximately equal to the frame period. A more quantitative demonstration of this will be found in section 2 of reference 1.

(U)   The RC time constant of an element of the bolometric layer is uniquely determined by the resistivity of the material. The dielectric constant of the material is unity because of the highly porous nature of the deposit. If ρ is the resistivity, d the thickness and A the area of the element, then in gaussian units we have

$$R = \rho\, d/A \quad \text{and} \quad C = A/(4\pi d)$$

Hence

$$RC = \rho/(4\pi)$$

Converting to practical units we find that an RC time constant equal to a frame time of 1/30 sec implies a resistivity of about 4×10^{11} ohm cm.

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2.4 Cooling

(U)   It is possible to choose the bolometric material so that the resistivity required for frame storage operation is obtained at room temperature. In this way tubes have been made to operate without any cooling. Such operation, however, involves a large degradation of contrast. This is because radiation is incident on the retina not only from within the solid angle, ω, subtended by the optical system, but also from the much larger solid angle, $4\pi-\omega$, not subtended by the optical system. This latter component of radiation contains no signal information at all and serves only to degrade the contrast.   To operate the tube in this manner is analogous to taking a photograph with just a lens and a photographic film but no camera box to prevent fogging of the film by light not coming through the lens. In the case of the Thermicon the unwanted component of radiation incident on the retina can be suppressed by employing a tube configuration similar to that illustrated schematically in Fig. 1. The G3 electrode of the gun is extended so as to form an enclosure around the retina with an aperture that just matches the angular aperture of the optics. The G3 enclosure is cooled by a continuous flow of liquid nitrogen through a cooling duct built in at the front end of the enclosure. When the temperature of the G3 enclosure reaches that of liquid nitrogen the radiation reaching the retina from this source is negligible compared with that from the optical aperture. Thus the contrast of the image on the retina has been restored. It should be noted that the configuration shown in Fig. 1 represents an extremely efficient cooling technique. The only part of the tube that is cooled is the G3 assembly. Since this is internal to the vacuum envelope of the tube, it is very well insulated thermally. As a result, the cooling capacity required is minimal (cf section 8.5). In addition, since the tube envelope remains close to room temperature, problems associated with condensation of moisture on the the tube window and other optical elements are minimized.

(U)   A detailed analysis of the effects of cooling on the contrast sensitivity of a bolometric sensing layer has been given in Part 1, section 4 of reference 2. From equation (8) of this reference, we see that the

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temperature, T_s, to which the sensing layer of the Thermicon is cooled is given by

$$T_s = (\frac{f}{8F^2})^{1/4} T \tag{1}$$

where T is the average temperature of the scene, f is the transmission factor of the cooled filter (not shown in Fig. 1 but present in the tube for the reasons discussed in reference 2) and F is the F-number of the optical aperture. In the cooled Thermicon tube the filter is 1/16" thick barium fluoride which transmits approximately 50% of the 300°K black body spectrum, so that f = 1/2. The aperture corresponds to F = 0.75. Substituting these values into equation (1) above, and using T = 300°K, we find for the sensing layer temperature

$$T_s = 175°K \tag{2}$$

The bolometric material must be chosen to have the proper resistivity for frame storage operation ($\sim 4 \times 10^{11}$ohm cm) at this temperature.

(C)   To determine the gain in contrast to be expected from cooling the Thermicon tube, we refer again to reference 2. The sensing layer temperature contrast, dT_s/T_s, for the cooled tube is given in terms of the temperature contrast in the scene, dT/T, by equation (11) on page 22 of reference 2:

$$\frac{dT_s}{T_s} = 1.4 \, \epsilon\eta \, \frac{dT}{T} \tag{3}$$

For the uncooled tube, the corresponding equation is (cf page 26, ref.2)

$$\frac{dT_s}{T_s} = \frac{1.4}{8F^2} \, \epsilon\eta \, \frac{dT}{T} \tag{4}$$

Comparison of equations (3) and (4) above shows that the cooling results in a contrast gain of a factor of $8F^2$. For a 0.75 optical aperture (F = 0.75), this factor becomes 4.5. This figure corresponds very closely with the observed relative performance of cooled and uncooled tubes made on this contract.

(C)   Although the cooling increases signal contrast, it has an adverse effect on spatial resolution and response time. The MTF of the Thermicon retina is given by[3]

$$MTF = (1 + \frac{n^2}{n_o^2})^{-1} \tag{5}$$

where

$$n_o = \frac{1}{2\pi} \sqrt{\frac{8\varepsilon\sigma T_s^3}{k\delta}} \tag{6}$$

In these equations, n is the line frequency (cycles per unit distance on the retina), ε is the emissivity of the retina, σ the Stephan Boltzmann constant, $k\delta$ the equivalent thermal conductance (thermal conductivity x thickness) of the retina, and T_s the retina temperature as previously. Putting $n = n_o$ in (5) gives MTF = 1/2. Hence the parameter n_o is simply the line frequency for which the MTF is 1/2. Equation (6) shows that n_o varies as the 3/2 power of the retina temperature. In the cooled Thermicon the retina temperature is 175°K (cf equation 1) and in the uncooled tube it is 300°K. Hence the resolution (expressed as line frequency for any given value of MTF) is better by a factor $(300/175)^{3/2}$ = 2.2 for the uncooled tube.

(C)   The thermal response time of the Thermicon retina is given by[4]

$$\tau = \frac{ms}{8\varepsilon\sigma T_s^3} \tag{7}$$

where m is the thermal capacity (mass x specific heat)of unit area of the retina. Thus for the uncooled tube the response time is shorter than for the cooled tube. However the difference is not as great as equation (7) would indicate since in the uncooled case the speed of response is limited by the frame time and not the thermal time constant of the retina.

3. Design and Fabrication of Sealed Tubes

(U)   During the contract a successful design for a sealed version of
the cooled Thermicon tube was developed. The structure of the tube can be
most readily understood by reference to Fig. 2, which is a photograph of
the various parts from which the tube is assembled. The heart of the
structure is the electron gun and cooling duct assembly, shown in the
upper center of Fig. 2. The upper portion of this unit consists of the
triode section (cathode, G1 and G2) of a conventional 1 inch electromag-
netic vidicon gun. This section is purchased, pre-assembled on a vidicon
base and pumping stem, from the Westinghouse Electron Tube Division in
Elmira, N.Y. The lower portion of the gun consists of a special coolable
G3 electrode. In the region where deflection of the electron beam
takes place, this electrode consists of a thin-walled low conductance
nichrome sleeve, as in the conventional vidicon, in order to minimize
neutralization of the deflection field by eddy currents induced
in the G3 electrode. Two copper cooling bars, extending up from the
lower end of G3, are brazed, one on either side, to the nichrome sleeve.
In the upper end of the G3 electrode a slit is cut in a plane containing
the axis of the sleeve and at right angles to the plane of the cooling
bars. This slit interrupts the low conductance loop that would otherwise
be formed by the cooling bars and the connection between them at the
upper end of G3. When the plane of the bars is properly oriented with
respect to the axis of the deflection field, this arrangement permits
effective cooling of the entire G3 electrode with acceptably low reduc-
tion of deflection field. The remainder of the G3 electrode is made of
copper, for more effective cooling. A liquid nitrogen reservoir is built
into the wall near the lower end. In operation, liquid nitrogen is
circulated through this reservoir via thin walled stainless steel tubula-
tion. The lower end of the gun is supported in the tube by a spider
consisting of three strips of thin stainless steel. The inner ends of
the strips are brazed to the copper G3 electrode and the outer ends are
spot welded to the back flange after insertion of the gun into the glass
stem or envelope. The assembly is jigged during this operation so that

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the spider then holds the gun on axis. The retina holder assembly is
inserted through an aperture in the lower end of the G3 electrode.
The diameter of this aperture is chosen to subtend at the center of the
retina, an angle corresponding to F/0.75. This aperture thus forms the
cooled aperture stop of the system. The inside surface of the G3 elec-
trode is coated with carbon black to reduce reflection of infrared radia-
tion. The outside surface of G3 and the inner surface of the envelope
are gold plated to reduce radiative heat input to G3.

(U)   The retina holder assembly is shown in the lower portion of
Fig. 2. On the left is seen the holder itself. This consists of a
copper sleeve threaded on the outer surface. A thin silver lining is
brazed to the inner surface of the holder. Near the lower end, the
inside diameter of the holder is counterbored to leave the lining in
this region independent of the copper sleeve. This leaves the silver
with sufficient mechanical flexibility to permit a barium fluoride disc
to be sealed with silver chloride into the lower end of the silver. The
flexibility prevents cracking of the barium fluoride both during the
sealing operation, when it is heated to 450°C, and during operation of
the tube, when it is cooled to liquid nitrogen temperature. The barium
fluoride disc serves as a cooled infrared filter. It is transparent in
the 8-13 micron atmospheric window but cuts out the longer wavelength
radiation arising from emission by the elements of the optical system.
It thus permits additional cooling of the retina without attenuation of
incoming signal radiation. Next to the retina holder in Fig. 2 is the
video signal contact ring. It is inserted into the holder with the two
short leads projecting through two holes cavitated in the barium fluoride
disc. The retina is then inserted into the holder so that its supporting
ring makes contact with the video signal contact ring. The lava insulator
is inserted next, with the counterbore facing down. The video signal
contact ring and the retina fit into this counterbore so that both are
electrically insulated from the retina holder. Next to be inserted is the
wall screen, followed by a beam limiting aperture. The purpose of the
latter is to prevent the electron beam from scanning too close to the edge
of the retina. In the deposition of the bolometric layer on the retina,

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an edge effect is encountered whereby the thickness of the layer is greatly reduced close to the edge. If the electron beam lands in this region, an objectionably bright ring is produced on the monitor display. The diameter of the beam limiting aperture is 5/8", which is therefore also the useful retina diameter. The final item to go into the retina holder is a spring which maintains positive contact between the retina and the video signal contact ring while taking up any differential contraction of the parts during cooling of the tube. The retina holder is screwed into the open end of the G3 assembly. The use of a screw joint in a sealed tube is somewhat unconventional. However, a very good thermal contact between the holder and the G3 electrode is required and brazing is not possible after retina insertion. Measurements show that the screw threads in copper provide excellent thermal contact, and with proper venting of the threads, no vacuum problems have been encountered.

(U)   The electron gun and cooling duct assembly is inserted into the back flange and stem assembly. The glass stem is sealed to the gun base, the stack plug on the liquid nitrogen lines is welded into the upper end of the stack in the back flange and the spider spot welded to the back flange. All the parts except the retina are then subjected to a prolonged vacuum bake. Immediately after the vacuum bake, the retina and other pieces are assembled into the holder which is screwed into place. The front of the tube is then closed by welding the window assembly to the back flange. The tube is then sealed to the pumping system and evacuated with a minimum of delay.

(U)   Fig. 3 is a photograph of the first sealed cooled Thermicon tube taken after assembly and processing were completed. The two structures protruding from the back flange are the liquid nitrogen cooling lines and the feedthrough terminal carrying the video output. The reflecting surface on the inside of the envelope for radiative shielding of the G3 assembly is also visible.

(U)   A total of 20 sealed cooled Thermicon tubes were constructed. All of them conformed closely to the design described above with the exception that in tubes #6 through 20 the barium fluoride window was replaced with one fabricated from Irtran-4. This change was made partly because of the superior transmission of the Irtran-4 at the long wavelength end of the atmospheric window, and partly because the lower dispersion of the Irtran-4 in this region made achromatization of the optical system easier to achieve.

4. Preparation of Retinas

(U)   The general structure of the Thermicon retina has already been described in section 2.2. A number of problems arose in connection with the fabrication of this structure. These were solved during the course of the contract but not, unfortunately, before many of the tubes had already been completed. As a result, only a few tubes made near the conclusion of the work incorporated fully satisfactory retinas.

(U)   One of the most serious problems encountered was a high rate of breakage of the nitrocellulose support films. In some cases this occurred after the incorporation of the retina into a sealed tube, resulting in loss of the tube. The trouble was eventually traced to the solvent used in the preparation of the nitrocellulose lacquer. The procedure for making the films is to dissolve solid nitrocellulose in a solvent to form a lacquer. A drop of the lacquer is dropped onto the surface of clean water. The lacquer spreads out, the solvent evaporates and a film of nitrocellulose remains. The film is picked up from the surface of the water on a metal ring. The thickness of the film is determined by the amount of nitrocellulose in a drop and the area over which the lacquer spreads. The lacquer solvent contains many highly volatile components and consequently its composition can change appreciably during limited periods ot storage. Apparently, this composition is critical for the preparation of satisfactory films. Only when we adopted the practice of making fresh solvent each time films were prepared were we able

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to make films that were sufficiently thin to give acceptably low heat spread and at the same time were mechanically durable.

(U)   Following fabrication, all of the retinas were tested in a demountable cooled Thermicon tube. A defect commonly observed in these tests was the appearance of a number of white spots in the kinescope presentation. A remarkable characteristic of these spots was that their intensity depended not on the applied sensing layer voltage but rather on the magnitude of the beam current. It was discovered that these spots correlated with very small pinholes in the retina. These could be observed in the retina itself by examination under a low power microscope. As the scanning beam passes over one of these holes, the beam passes straight through and all the electrons are collected on the far side of the retina, possibly on the support ring, to produce a saturated signal. This explains the dependence of intensity on beam current rather than sensing layer voltage. The creation of these pinholes was eventually traced to the process of deposition of the gold black layer. During the evaporation of the gold from a tungsten filament, very small drops of molten gold would be ejected from the filament. Some of these would strike the nitrocellulose substrate, pass straight through and leave a pinhole. This process was found to be greatly dependent on the state of cleanliness of the tungsten filament and the gold. Although we were never able to suppress the ejection of droplets altogether, by careful cleaning of the filament and gold prior to deposition of gold onto the substrate, we were able to reduce the effect and obtain a corresponding reduction of white spots in the video picture.

(U)   A very serious problem that was eventually traced to the bolometric layer of the retina was the occurrence in virtually all of our sealed tubes of a severe degree of shading. By the term shading is meant a variation of video current with position in the field of view when the tube is viewing a field of uniform temperature. The presence of shading seriously degrades the performance of the tube because the different levels of video current coming from different regions of the retina prevent the operator from setting the camera controls in such a way as to optimize the contrast simultaneously in all regions of the retina. Specifically, it becomes impossible to set the black level at the background current level if the background

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current level varies from one region of the retina to another. Under these circumstances the operator either has to run the system at low contrast so as to accommodate the total variation of current within the range of black to white, or he can enhance the contrast in a small region of the field driving the remainder of the picture either to blackness or to saturation.

(U)   For a long time it was believed that this shading was not caused by a nonuniformity in the sensing layer, since the shading was not detected in the demountable Thermicon when the retinas were tested there, but showed up only in the sealed tubes. Consequently, other sources of shading were sought, but without success. These investigations are described in detail in sections 3.1 to 3.9 of reference 5. Eventually it was realized that shading due to sensing layer nonuniformity would be difficult to detect in the demountable tube for two reasons. The first was that a considerable degree of optical vignetting was present in the demountable tube. This would tend to mask the effect of shading due to retina nonuniformity. The second reason was that the cooled enclosure aperture in the demountable tube was somewhat larger than in the sealed tube (which was carefully matched to the optics). As a result the retina temperature was slightly higher in the demountable than the 175°K in the sealed tubes. The sensing layer resistance was therefore lower in the demountable tube and hence the operating voltage was lower. Under these circumstances the alignment controls provided in the beam deflection circuitry are much more effective in compensating for any shading present in the sensing layer. For the alignment controls can provide the equivalent of only a limited variation of applied voltage from one region of the retina to another. This will represent a large percentage correction when the applied voltage is low, as in the demountable tube, but only a small percentage correction when the voltage is high, as in the sealed tube.

(U)   This realization, along with our failure to discover other sources of the shading, directed attention once more to the possibility that the shading might be due to a nonuniformity in the sensing layer. Strong corroboration of this possibility was provided by observations of the behavior of the shading in tube #16, which was typical of many, as the degree of cooling of the tube was varied. It was found that when

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the flow of liquid nitrogen was interrupted and the tube permitted to
warm up towards room temperature, the degree of shading steadily
decreased along with the resistance of the sensing layer. It was very
difficult to believe that electron optical effects, such as angle of
incidence of the electron beam, would be temperature dependent. Indeed,
the only parameter one would expect to vary with temperature was the
sensing layer resistance, so that the shading, which also varied, was
presumably associated with this parameter.

(U)   Accordingly, the process of evaporation and deposition of the
bolometric material was carefully reviewed for possible sources of non-
uniformity. The process was customarily performed on seven retinas
simultaneously. The retinas were mounted in the evaporator on a circular
table. One retina was located in the center of the table and the remain-
ing six were distributed around a circle near the periphery of the table.
The crucible from which the bolometric material was evaporated was
located under the table and about two-thirds of the way out from the
center of the circle of peripherally located retinas. During evaporation
the table was rotated about a vertical axis through its center so that
each of the peripheral retinas spent the same amount of time in the region
of the crucible. As a result of the rotation of the table, the peripheral
retinas moved with an orbital motion, coming close to the crucible once
each revolution, while the center retina merely rotated about an axis
through its center and remained at constant distance from the crucible.
A moment's thought about this motion shows that any nonuniformity in the
incidence of evaporated material in the plane of the table would have
resulted in a radial variation of thickness of the deposit on the center
retina but a nearly linear or one dimensional variation on the six
peripheral retinas. Now of the last several tubes made up to that time,
just one of them had exhibited a purely radial shading pattern. This
tube was #12. All of the others had exhibited a one dimensional shading
pattern. On going back over our records of the retinas used in these
tubes we found that tube #12 was the only one with a retina that was
prepared in the center position in the evaporator table. This strongly
suggested that the shading observed in the sealed tubes arose in the

evaporation and deposition of the bolometer.

(U)   To obtain more direct evidence of shading in the retinas, a
new batch of seven was made and subjected to the most careful examination.
The standard procedure outlined above was used for the evaporation of the
bolometer. After evaporation the retinas were examined visually while
still in the evaporator table. If viewed by transmitted light under con-
ditions of strong illumination, one dimensional shading could be detected
in the optical transmission of every one of the six peripherally mounted
retinas, the light region of the deposit being directed away from the
center of the table in each case. The center mounted retina showed very
slight radial shading but no one dimensional shading. These observations
were confirmed by quantitative measurements with a narrow beam optical
densitometer. Each one of the seven retinas was then tested in the
demountable Thermicon. In these tests the alignment current through
both pairs of alignment coils was set at zero. When this was done, one
dimensional shading in video current was observed in every one of the
six retinas from peripheral positions in the evaporator. The magnitude
of the shading was comparable to that observed in our sealed tubes, i.e.
a factor of 2 or 3 variation in current at a given retina voltage.
Furthermore, the orientation of the shading pattern matched exactly with
that of the visually observed shading in optical transmission for all
six of these retinas. The retina from the center position in the
evaporator showed no one dimensional shading in the demountable tube.
Any radial shading was of course masked by the vignetting discussed
earlier.

(U)   The above observations provided conclusive evidence that the
shading in our sealed tubes was produced in the evaporator during deposi-
tion of the bolometer. A new evaporator table was therefore designed to
eliminate the effect. The new table is illustrated in the photographs
shown in Figs. 4 and 5. The retina substrates are each mounted in a
horizontal spur gear. The gears are located at uniform intervals
around a circle near the periphery of the table top. The table top
is supported on a ball race and is rotated about an axis through its

center by a magnetic drive through the glass wall of the bell jar. At the periphery r   circular table the spur gears mesh with a large internal ring gear, which is held fixed as the table top rotates. The spur gears thus roll around the inside of the ring gear causing the retina substrates to spin during their orbital motion. The gear ratios are such that each retina spins 3-2/7 rotations in one orbital cycle. Thus in successive passages through a given point on its orbit a retina assumes seven different orientations before repetition of the pattern. In this way the nonuniformity pattern, which is radial about the axis of rotation of the table, is averaged out in each retina.

(U)   Retinas prepared on the new evaporator table showed vastly improved shading characteristics. They were used in the last four cooled sealed tubes made on the contract, nos. 17-20.

5. Optical System

(C)   The requirements imposed by the cooled Thermicon on the optical system were somewhat unusual. The contract specified a limiting angular resolution of 0.4 milliradians. With the limiting resolution on the retina fixed by thermal conductance at about 0.1 mm, this required a focal length of approximately 10 inches. At the same time the F-number of the system had to be unusually low. The contrast sensitivity of the cooled tube does not depend on F-number, as is shown by equation (3) on page 8, provided the aperture of the cooled enclosure is "filled" with optical system. However, according to equation (1), the temperature, T_s, to which the sensing layer is cooled does depend on the F-number of the cooled aperture. As F is made larger, i.e. the aperture in the cooled enclosure is made smaller, the value of T_s decreases. A minimum practical value of T_s occurs at about 175°K for two reasons. The first is that below this temperature the thermal response time of the retina, which varies as T_s^{-3} according to equation (7), becomes unacceptably large. The second reason is that we have been unable to discover

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bolometric materials which retain their high sensitivity at temperatures below 175°K. Typically, these materials go extrinsic and lose their temperature sensitivity on cooling long before this temperature is reached. GeTe, the material used in the cooled Thermicon retina, is an exception. In the smoke evaporated form it remains essentially intrinsic and also has, at 175°K, a resistivity suitable for frame storage operation (cf section 2.3). In order to achieve the required temperature of 175°K, equation (1) tells us we need an aperture in the cooled enclosure of the tube corresponding to an F-number of 0.75. The tube is therefore designed with such an aperture. In order to realize the full contrast sensitivity predicted by equation (3), this aperture must be matched by that of the optical system.

(U)   The above considerations led us to a requirement for an F/0.75, 10 inch focal length, optical system to operate in the 8-14 micron band of the infrared spectrum. No such system was commercially available. However, the Westinghouse Research Laboratories had recently developed an automatic computer program for the optimization of optical system designs. We therefore undertook the design of a system conforming to the above specifications for use with the cooled Thermicon. A difficulty encountered in the design of the system was the location of the system stop. Ideally, this should be located in image space in coincidence with the aperture of the cooled enclosure in the tube. Any other location of the stop would cause vignetting as a result of parallax between the stop and the cooled aperture. However, it was soon found that this position of the stop, which was unusually close to the image plane, forced the entrance pupil of the system to fall well behind the primary mirror. As a result, vignetting, avoided at the exit pupil, occurred at the entrance pupil unless the diameter of the primary was made much larger than the 13-1/3 inches required on the basis of F-number and focal length alone. Such a large primary was ruled out as unacceptable. A diameter of 13-1/3 inches was decided on as the largest that could be tolerated. With this constraint, the vignetting between the primary and the entrance pupil was very serious when the stop was located at the

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cooled aperture of the tube. A much more satisfactory compromise
between vignetting at the entrance and exit pupils was finally achieved
by making the system telecentric on the image side. Such a system has
the property that the principal rays, i.e. those that pass through the
centers of the entrance and exit pupils, from all points in the field
of view emerge in image space parallel to the axis. This is equivalent
to locating the exit pupil at infinity. By this means it was possible
to reduce the vignetting loss at full field to only 30% with a 13-1/3
inch diameter primary.

(U)   The optical configuration resulting from the above design
procedure is shown in Fig. 6. The primary mirror is a rotationally
symmetric aspheric with a diameter of 13.33 inches. The secondary
mirror is also aspheric and has a clear aperture of 7.41 inches. The
diameter of the mechanical support structure for the secondary is 8.24
inches, so that about 40% of the incident radiation is obscured. The
two mirrors are followed by a pair of corrector lenses fabricated from
germanium. Both lenses have spherical surfaces. Because of the very
high refractive index of germanium, antireflection coatings on the sur-
faces of the lenses are essential. A three layer coating optimizing
the transmission in the 8-14 micron band was used. The primary mirror
was provided with a 4.5 inch diameter axial hole to permit insertion of
the Thermicon tube into the system. The window of the tube is represented
by surfaces 7 and 8 in Fig. 6.

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6. Thermicon Camera

(U)   When the cooled Thermicon system, built under this contract, was delivered to NVL in January 1970, a manual describing in detail the electronic circuitry of the video camera was delivered along with the system. Only a general description of the system will therefore be given here. The system is built into a single tripod mounted unit. The optical system is mounted atop the tripod on a gear driven pan-tilt head. Bolted to the back of the optical system is the camera head, which contains the Thermicon tube mounted in the deflection and focussing yoke, the cooling system and the video preamplifier. The yoke and cooling system are mounted on a moveable carriage driven by a screw. This provides a fine control of the degree of insertion of the tube into the optical system for adjustment of optical focus. Movement of the cooling system with the tube eliminates the need for flexibility in the liquid nitrogen lines. The reservoir for the liquid nitrogen supply consists of a 2.5 liter metal dewar which hangs from the carriage out of the bottom of the camera head. An adjustable relief valve controls the pressure in the dewar. As this valve is closed down the pressure in the dewar rises due to slow boiling of the nitrogen, and liquid nitrogen is automatically forced through the system and into the tube. The rate of flow is controlled by adjusting the relief valve. After passage through the Thermicon tube the nitrogen is passed through a thermostatically controlled heater which warms it up to room temperature to provide a source of ultra-dry gas. This is blown over the tube face and through the camera head to eliminate any undesirable frosting or condensation. The video preamplifier is a specially designed FET unit giving state of the art performance with respect to low noise and high input impedance. The amplified video signal from the preamplifier is fed via 75 ohm coaxial cable to the main video amplifier which is located in the camera control unit (CCU). The CCU is mounted on one leg of the tripod and contains all of the camera controls. The circuitry is subdivided on plug in circuit boards for easy servicing. Mounted on the tripod leg alongside the CCU is an 8-inch monitor. This arrangement enables the operator, sitting before the tripod, to reach all controls and view the

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output picture from a single convenient position. The tripod is mounted
on a caster dolly so that the entire system may be easily moved.

7. Video Correlator

(U)   The camera system described in the previous section can be
operated as a complete independent unit. However, the system performance
is greatly enhanced when it is used in conjunction with an accessory unit
called the video correlator. The function of the video correlator is to
increase the signal contrast by subtraction of the background component
from the video signal. Whereas the contrast or pedestal control in the
camera can subtract only a uniform background level from the entire pic-
ture, the video correlator can subtract a nonuniform background.

(U)   The correlator consists essentially of a multi-track magnetic
disc video recorder and video processing circuitry. The background dis-
tribution of video current is stored by the correlator by recording a
number of video frames, each on a separate circular track of the disc,
with the optics capped to provide a uniform infrared input. The cap is
then removed from the optics and the stored background video is sub-
tracted by the processing circuitry from each live video frame. The
video output is then equal to the difference between the signal and the
background at each point of the picture. In this way the shading com-
ponent of video current is removed from the output and the contrast
increased over the entire picture.

(U)   To achieve satisfactory subtraction, accurate spatial registra-
tion between the live video and the stored background is important. This
is achieved by synchronizing the deflection generators in the camera
system with the rotation of the disc in the correlator. Synchronizing
signals are permanently recorded at regularly spaced points around a track
of the disc reserved for this purpose. As the disc rotates, this track
provides sync pulses that are used to trigger a sync generator built into
the correlator. The output of this sync generator is in the form of
vertical and horizontal drive pulses that are fed to the deflection

generators in the camera system. The camera system incorporates its own sync generator that is used when the camera is operated independently without the correlator. When the correlator is used, the two sync generator boards are simply unplugged from the CCU and vertical and horizontal drive cables from the correlator plugged in.

(U)   As important as spatial registration is linearity in the recording and playback processes. Any distortion of video amplitude will result in only partial cancellation of the background. To ensure the necessary linearity, the video signal is used to modulate the frequency of a carrier wave. It is this frequency modulated wave that is actually recorded on the disc. The deviations of frequency, representing video amplitudes, are faithfully reproduced in the recording and playback processes. FM detectors recover the video signal during playback.

(U)   The disc has eight tracks available for recording video information. Thus up to eight frames of background video may be stored simultaneously on the disc. The reason for this provision is to eliminate the objectionable effect of the recorded noise that occurs when only one frame is recorded. Superimposed on the video signal of every frame there is naturally an unavoidable level of random noise. The human eye, observing the unprocessed live video output displayed on a monitor, effects a reduction of the rms noise level by visual integration of the noise over a period equal to its response time, which is equivalent to about eight frame periods (1/4 second). The reduction in noise level depends on the fact that there is no correlation between the noise waveforms of successive video frames. The waveform thus gets "smeared out" in the integration. However, if only a single frame of background video is recorded, and this frame is subsequently subtracted from each successive live video frame, the noise pattern in the recorded frame will be the same in each subtraction, giving rise to a stationary noise pattern in the output video. Since this pattern is identical in each frame, no amount of visual integration will reduce the amplitude of the pattern. Hence the noise recorded in the background frame will produce

a stationary grain pattern in the picture with an amplitude that is large compared with the rms amplitude of random noise observable in the picture. This degradation of the output picture is eliminated by recording not one but several consecutive background frames. The number of frames is preselected by switching in the n tracks to be used. When the record button is pushed the correlator automatically records the next n frames of video, one on each of the selected tracks. When the difference button is then pushed, the correlator subtracts from the incoming video the average of the n stored video frames. In the averaging of the stored reference frames the recorded noise pattern is reduced in amplitude, since the noise waveform is different in each of the n frames. With n as large as 8 the fixed pattern noise is reduced to the same level as the rms noise seen in the live video, which is also integrated (by the eye) over about eight frames.

(U)   Work on the development and construction of the video correlator was started when the shading problem in our sealed tubes created a crucial need for background subtraction. When the new evaporation technique, described in section 4, greatly reduced the shading in the retinas, the need for the correlator was no longer as vital. However, it was found that even with the new more uniform retinas, use of the correlator still produced a significant improvement in performance. Partly this was due to removal of residual shading still present in the new retinas. Also it was found that the spatial registration accuracy was sufficiently good to permit the removal of high spatial frequency nonuniformities that gave rise to fine grain in the uncorrected picture. To take advantage of this possibility it is necessary to update the reference background frames periodically--perhaps every 10 or 15 minutes. This is because the sweep circuits of the camera are not stabilized and long term drift in the raster centering and size causes a gradual misregistration between live video and reference frames. However, updating is such a simple and rapid operation that this necessity is not much of a disadvantage. To update, one merely covers the optics, presses the "record" button, uncovers the optics and presses the "subtract" button, all of which takes but a few seconds.

(U)   Following updating of the reference there are a couple of adjustments that can be made if necessary. One is a front panel control of a variable delay line which provides fine adjustment of horitontal registration. The other is the so-called balance control. This controls the relative amplitudes of the live video and the background reference going into the difference amplifier. Proper adjustment of this control produces complete subtraction of the background. A good way to set this adjustment is to do it with the optics capped and adjust the control for no video output.

(C)   An interesting application of the video correlator is for image motion detection. This is achieved simply by leaving the optics uncapped during updating of the reference. When this is done the reference video that is subtracted contains not only the instrumental background but also the scene signal at the time of updating. Hence, in the difference picture no video will appear until something in the scene moves. One then sees on the monitor a positive image of the moving target together with a corresponding stationary negative image in the initial position of the target, all in a blank background. This mode of operation greatly enhances the detectability of moving targets.

(U)   Photographs of the video correlator are shown in Figs. 7 and 8. A manual on the video correlator has been prepared. This gives a detailed description of the unit along with operating and servicing instructions. A copy of the manual will be delivered to NVL in addition to this report.

8. Performance

8.1 Field Tests

(U)   In order to judge the performance of the Thermicon system and
to permit comparisons with the performance of competitive systems, the
contract provided for a number of field tests of the system. These were
conducted at the U.S. Army Proving Ground, Ft. Belvoir, Va. under the
supervision of the contract technical monitor, J. R. Moulton of NVL. Both
NVL and Westinghouse personnel participated in these tests. The first
test was held in October, 1968. Subsequent tests were conducted in
February, May and July of 1969, and in January and March of 1970. Thus
the complete seasonal cycle of weather conditions was covered in the test-
ing program. The tests were conducted during the hours of darkness to
ensure conditions appropriate to the night vision application.

(U)   A permanent record of the performance of the Thermicon system
in these tests was made by NVL in the form of video tape recordings of
the imagery obtained, along with a simultaneous audio commentary by the
contract technical monitor. These tapes provide a faithful and detailed
documentation of the test results. Consequently, a detailed description
of the results is unnecessary and will not be attempted here.

(C)   The targets used in the tests were personnel and/or vehicles,
stationed or moving at various distances from the Thermicon up to a dis-
tance of about 1000 meters, which was the maximum line of sight range
available in the test area. Vehicles were easily seen with the system
at all of these ranges. Personnel could be seen with increasing difficulty
as the maximum range of 1000 meters was approached. They were still
detectable as small blobs at 1000 meters. The detectability of personnel
at this distance was somewhat improved by motion detection with the
correlator as explained at the end of the preceding section. Observations
were also made of terrain features such as trees and buildings, which were
usually clearly visible. An exception was noticed following prolonged
rainfall. The rain apparently washes down the terrain reducing all its
features to a very uniform temperature. Very little in the way of terrain
features is then visible to the Thermicon. However, under these conditions

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targets such as personnel and vehicles with warm parts stand out with great clarity against the uniform background. On some nights cloud formations were clearly visible with the Thermicon.

8.2 Sensitivity

(U)   In addition to the field tests at Fort Belvoir, a number of laboratory measurements relating to the performance of the Thermicon system were made at the Westinghouse Laboratories. In early work on the cooled demountable Thermicon, performed under previous contracts, not all of the additional sensitivity expected to result from cooling was in fact realized. One of the objectives of the present contract was to achieve the full theoretical sensitivity of the cooled tube. Early in this con- tract it was discovered that the reason for the disappointing performance of the early demountable tube was inadequate cooling of the G3 enclosure. Whereas that end of the enclosure near the liquid nitrogen duct was being cooled essentially to liquid nitrogen temperature, the far end towards the gun cathode was not, due to insufficient thermal conduc- tance along the length of the G3 structure. In the design of the sealed cooled tube, careful attention was paid to this point. Heavy copper cool- ing bars were brazed to the G3 electrode to ensure cooling of the entire length of the enclosure. Only when this is done is all of the radiation from G3 onto the sensing layer suppressed.

(U)   To compare the sensitivity of the cooled Thermicon tube with the theoretically expected value involved essentially two steps. The first was a measurement of the temperature coefficient of resistance of the bolometric material. The second was a measurement of the output current of the tube as a function of object temperature. From this second measurement an effective temperature coefficient could be deduced and compared with the known temperature coefficient of the material.

(C)   The bolometric material used in the cooled Thermicon is GeTe, a IV-VI semiconducting compound. The electrical conduction process in such a material is due to the motion of thermally activated free carriers. The conductivity (or current at constant voltage) would therefore be expected

to depend exponentially on reciprocal temperature according to an equation
of the form

$$i = i_o \, e^{-E/kT} \tag{8}$$

where i is the current through the material, T is the absolute temperature
of the material, k is the Boltzmann constant and E is the activation energy
characteristic of the material. Taking logarithms of both sides of (8)
shows that

$$\log_{10} i = - \frac{E}{kT} \log_{10} e + \log_{10} i_o \tag{9}$$

Thus the logarithm of i should be a linear function of the reciprocal
temperature (1/T) with a slope of $-(E/k) \log_{10} e$. The dependence of current
on temperature in a sample smoke layer of GeTe was measured directly by
enclosing the sample in a cryostat, the temperature of which could be
adjusted throughout the range from room temperature down to liquid nitrogen
temperature. The results of this experiment are shown in Fig. 9, in which
$\log_{10} i$ is plotted as a function of reciprocal temperature for several dif-
ferent values of voltage applied across the thickness of the layer. The
linearity of each plot confirms the form of equations (8) and (9). From
the slope of each line an experimental value of the activation energy, E,
may be derived. The values of E thus obtained are noted in Fig. 9. The
GeTe layer in the Thermicon retina is operated at an applied field of about
2 volts/micron. Hence the appropriate value of E is about 0.45 eV. The
temperature coefficient, α, may be obtained by differentiating either of
equations (8) or (9):

$$\alpha = \frac{1}{i} \frac{di}{dT} = \frac{E}{kT^2} \tag{10}$$

Substituting E = 0.45 eV and T = 175°K, the retina temperature in the
cooled Thermicon (cf equation 2 on page 8) we find a temperature coefficient
of

$$\alpha = 0.17 \text{ per } °K \tag{11}$$

i.e. a 17% change in resistance for each °K change in temperature.

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(C)   To compare the performance of the Thermicon tube with the above figure, the output current of one of our sealed cooled tubes was measured as a function of object temperature, the object in this case being a beaker of warm water. The results are shown in Fig. 10, in which the change in output current, Δi, is plotted as a function of ΔT, the temperature difference between the water in the beaker and ambient. From the slope of this curve one derives for the relative change in current per °C a value of

$$\frac{1}{i}\frac{di}{dT} = 1.8 \times 10^{-2}/°C \tag{12}$$

This is not the effective temperature coefficient of the sensing layer because the dT in this equation is the change in temperature of the water, not the change in temperature of the sensing layer, dT_s. These two quantities are related by equation (3) on page 8, from which we have

$$dT_s = 1.4 \, \varepsilon \, \eta \, \frac{T_s}{T} \, dT \tag{13}$$

ε, the effective emissivity of the beaker was measured to be 0.57 by comparing it (as a Thermicon object) with the cavity of an oven with blackened walls. η, the transmission coefficient of the optical system is the product of several factors:

$$\eta = 0.9 \times 0.8 \times 0.6 \times 0.75 \times 0.85$$
$$= 0.28$$

The first factor is based on the assumption of 95% reflection at each of the two mirrors in the optics. The second assumes a 90% transmission coefficient for each of the coated germanium lenses. The third factor (0.6) accounts for the 40% loss due to obscuration of the entrance pupil by the secondary mirror. The remaining two factors represent estimates of the transmission of the tube window and the cooled filter, respectively. Substituting the above values for ε and η into (13) and using $T = 300°K$ and $T_s = 175°K$ (cf equation (2) on page 8), we find

$$dT_s = 0.13 \, dT.$$

Hence, from (12),

$$\frac{1}{i}\frac{di}{dT_s} = \frac{1.8 \times 10^{-2}}{0.13} /°C = 0.14/°C \tag{14}$$

Comparing this with (11) we see that the output of the cooled Thermicon tube is compatible with the temperature coefficient of resistance of the bolometric material and reasonable assumptions concerning the radiation exchange between the object and the sensing layer.

8.3 Limiting Resolution

(C)   Tube No. 4 was used to make careful measurements of the limiting spatial resolution as a function of input signal level. This data is indispensable in estimating the performance of the tube in its intended application, viz. the night-time viewing of low contrast terrestrial scenes. In this application, objects within the scene are to be detected and recognized by a human observer. We therefore need to know the threshold of detectability of objects to such an observer. The specification of the performance of the system in terms of these thresholds has been objected to as unscientific on the ground that they involve a subjective element and cannot therefore be reproducibly measured. It has, therefore, been urged that the performance be specified in terms only of objectively defined parameters, such as modulation transfer function, noise equivalent temperature, etc., which do not require a subjective judgment for their measurement. While the pursuit of objectivity as a scientific ideal is to be commended, one must face the fact that at the present time there exists no theory relating the values of these objective parameters of a system to just what can be discerned by an observer using the system. Not only would such a theory have to deal satisfactorily with complex physical questions, such as the effect of the noise spectrum on the significance of parameters such as the noise equivalent temperature, but also physiological and psychological factors of the observation process would have to be included. The realization of such a theory is obviously not imminent. In the meantime, the only substitute for the

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theory, in the estimation of the value of a given system as an observational aid, is the direct experimental investigation of observational thresholds set by the system. Thus the very subjectivity of thresholds becomes a unique advantage, since it means that relevant subjective factors, inaccessible to the objective treatment, are included in the specification.

(U)   A satisfactory operational criterion for deciding at just what point an observer ceases to discern a given object was established by the following procedure. A number of resolution stencils are used, each stencil consisting of a set of regularly spaced parallel bars. One of these stencils is placed in front of the aperture of an oven. The temperature difference between the stencil and the oven is measured directly with a thermocouple having one junction attached to the stencil and the other to the oven. The thermal bar pattern formed by the stencil and oven is viewed with the Thermicon. The experimenter orients the stencil in front of the oven with the bars either horizontal or vertical. An observer, who views only the TV monitor and not the stencil directly, is asked to decide whether the orientation of the bars is horizontal or vertical. If he can really distinguish individual bars, the observer gives the correct orientation in 100% of a number of trials. If, on the other hand, he is guessing, his score would be expected to drop to 50%.

(C)   Fig. 11 shows the results of such an experiment. Each point plotted gives the result of 20 trials at a given line number. It will be seen that for line numbers below 4 line pairs/mm, the observer always scores 100%. Beyond this line number his score becomes erratic and always less than 100%. A remarkable feature of Fig. 11 is that the score remains, on the average, significantly greater than 50% for line numbers considerably greater than 4 line pairs/mm. Whether this represents extraction of residual information from a noisy picture or clairvoyance on the part of the observer, we do not know. However, this region of the curve is not important since an imaging system that provides correct recognition of a target with a frequency of less than 100% is not of military interest. Fortunately, the line number at which recognition of

the pattern ceases to be 100% reliable is very well defined. Thus, in
Fig. 11, the observer scores 100% in 20 trials at 4 line pairs/mm, but
cannot do this in any of 3 groups of 20 trials at 4 1/4 line pairs/mm.
The line number at which the score ceases to be 100% is taken as the
resolution limit.

(U)   By repeating this entire experimental procedure at a number
of different values of ΔT, the temperature difference between oven and
stencil, one can investigate how the limiting resolution varies with
input signal level. In this way, the data of Fig. 12 was obtained. As
expected, there is a strong dependence of resolution on signal level.
The intercept of the curve with the ΔT axis represents the smallest
temperature difference that can be seen with the system. This parameter
on its own, however, does not provide much information about the per-
formance of the device, since it refers only to objects that are very
large, i.e. that correspond to very low values of line number. The
curve of Fig. 12 also shows the futility of trying to express the
limiting resolution as a single number. Clearly the limiting resolu-
tion can be almost anything, depending on the signal level. The curve
as a whole, however, provides a fairly complete description of the ability
of the system to discern warm objects. All objects lying beneath the
curve are visible, all those lying above it are not.

(U)   In estimating the performance of the cooled Thermicon from
Fig. 12, it should be remembered that the data plotted represents the
performance of the whole system--optical system, tube and observer. As
noted in the figure, our T/2.3 optics was used in this case. If a faster
optical system were substituted then the performance would be correspond-
ingly improved, provided that the optics itself did not limit the resolu-
tion. In this case, the ΔT scale would be changed so that all the ΔT
values would be decreased in inverse proportion to the speed of the optics,
while ordinates remained unchanged.

8.4 Response Time

(C)   The response time of the cooled Thermicon was measured by
observing the decay of video output, frame by frame, when a warm object
is suddenly removed from the field of view. The video output was
observed with a line-selecting oscilloscope. A Polaroid camera was used
to photograph the oscilloscope trace. At a given instant the object
was obscured by a shutter and, simultaneously, the shutter of the camera
was opened and the next several oscilloscope traces photographed with a
single exposure. A typical oscillogram obtained in this way is shown in
Fig. 13. The successive traces indicate the output of the tube at
successive intervals each of 1/30 second following removal of the object.
The amplitude of the video signal, measured from this oscillogram, decays
as an exponential function of time. The associated time constant, i.e.
time to decay to 1/e of the initial value, is about 3 frames, or 1/10
second.

8.5 Cooling Load

(C)   A performance parameter of considerable practical importance
for a cooled tube is the cooling load, i.e. the load placed on the cooling
system by the tube. Our sealed tubes nos. 4 and 5 were both fabricated
with internal thermocouples brazed to the G3 enclosures to permit a study
of the effectiveness of the liquid nitrogen cooling. This also made
measurements of cooling load possible on both of these tubes. Two
independent methods of measurement were used on each tube. In both
methods the tube is cooled to operating temperature with all potential
sources of heat input, such as the deflection and focussing fields,
electron gun and electronics, turned on. Once an equilibrium tempera-
ture is reached, the flow of liquid nitrogen is interrupted and the
temperature of the G3 assembly continuously monitored. Immediately after
the flow of liquid nitrogen is cut off, the temperature remains constant
at liquid nitrogen temperature for a well defined interval of time. This
interval is the time taken for the liquid nitrogen to boil away from the
G3 reservoir or duct. Measurement of this time interval therefore gives

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directly the rate of consumption of liquid nitrogen by the tube. In
the calculation it is assumed that the G3 reservoir is completely
full of liquid at the instant the flow is shut off. In fact, however,
it may be that a portion of the volume of the reservoir is occupied by
gas at the outset, in which case the volume of liquid that boils away
in the measured time is somewhat less than that of the reservoir. The
method therefore gives an upper limit for the cooling load. After all
the liquid nitrogen has boiled away the temperature of the G3 assembly
starts to rise. By measuring the rate at which the temperature increases
and estimating the thermal capacity of the G3 assembly, one can calculate
the total rate of input of heat to the G3 assembly. This is equal to the
rate at which heat must be extracted by the coolant in order to maintain
the assembly at liquid nitrogen temperature. This gives a second inde-
pendent estimate of the cooling load. On tube no. 4 the results obtained
for the cooling load by measurement of the boiling time and by measurement
of the rate of rise of temperature were 2.2 watts and 1.8 watts respectively.
For tube no. 5 the corresponding results were 1.9 watts and 1.7 watts.
These results, all in the neighborhood of 2 watts, represent a very low
rate of consumption of liquid nitrogen, about 45 cc/hr. It should be
remembered that what was measured here was the internal consumption by
the tube itself. The results show that most of the liquid nitrogen is
consumed in the transfer system between the dewar and the tube. This is
to be expected since no effort was made to insulate the transfer lines.
In the present system it was found that 2 liters of liquid nitrogen would
permit about 5 hours operation of the system. This corresponds to a con-
sumption rate about ten times that of the tube itself. Thus a very
significant saving of nitrogen consumption could be made by engineering
a more efficient transfer system. It would appear entirely feasible to
run the system from a closed cycle mechanical cooler.

9. Uncooled Tubes

(C)   Late in the contract a modification was negotiated providing
for the fabrication of two uncooled Thermicon tubes in addition to the
cooled tubes. The purpose was to permit a comparison of the performance
of the cooled and uncooled tubes in the field tests at Fort Belvoir.
Unfortunately, funds were not available to support any significant amount
of development work on retinas for these tubes. Because of the different
operating temperature a different material was required for the bolometer.
During the contract extensive work was done developing methods for deposi-
tion of uniform smoke layers of GeTe for the sensing layers for cooled
tubes. For the uncooled tubes As_2Se_3 was used as the bolometric material.
The techniques developed for successful deposition of GeTe did not work satis-
factorily for As_2Se_3. As a result, the retinas for the room temperature
tubes were grainy and nonuniform. It is felt that development effort
similar to that spent on the cooled GeTe retinas would produce tubes more
representative of the potentiality of the uncooled tube.

(C)   Despite these shortcomings, both of the two uncooled tubes made
on this contract were operated during the field tests at Fort Belvoir.
The video correlator provided considerable assistance in compensating for
the bad grain and shading in these tubes. The sensitivity was observed
to be less than that of the cooled tubes by about the amount predicted by
equations (3) and (4) on page 8. The superior spatial resolution and
speed of response, predicted on page 9 for the uncooled tube, were also
noticed in these tests.

10.   List of Figures

Fig. 1—Schematic of Cooled Thermicon
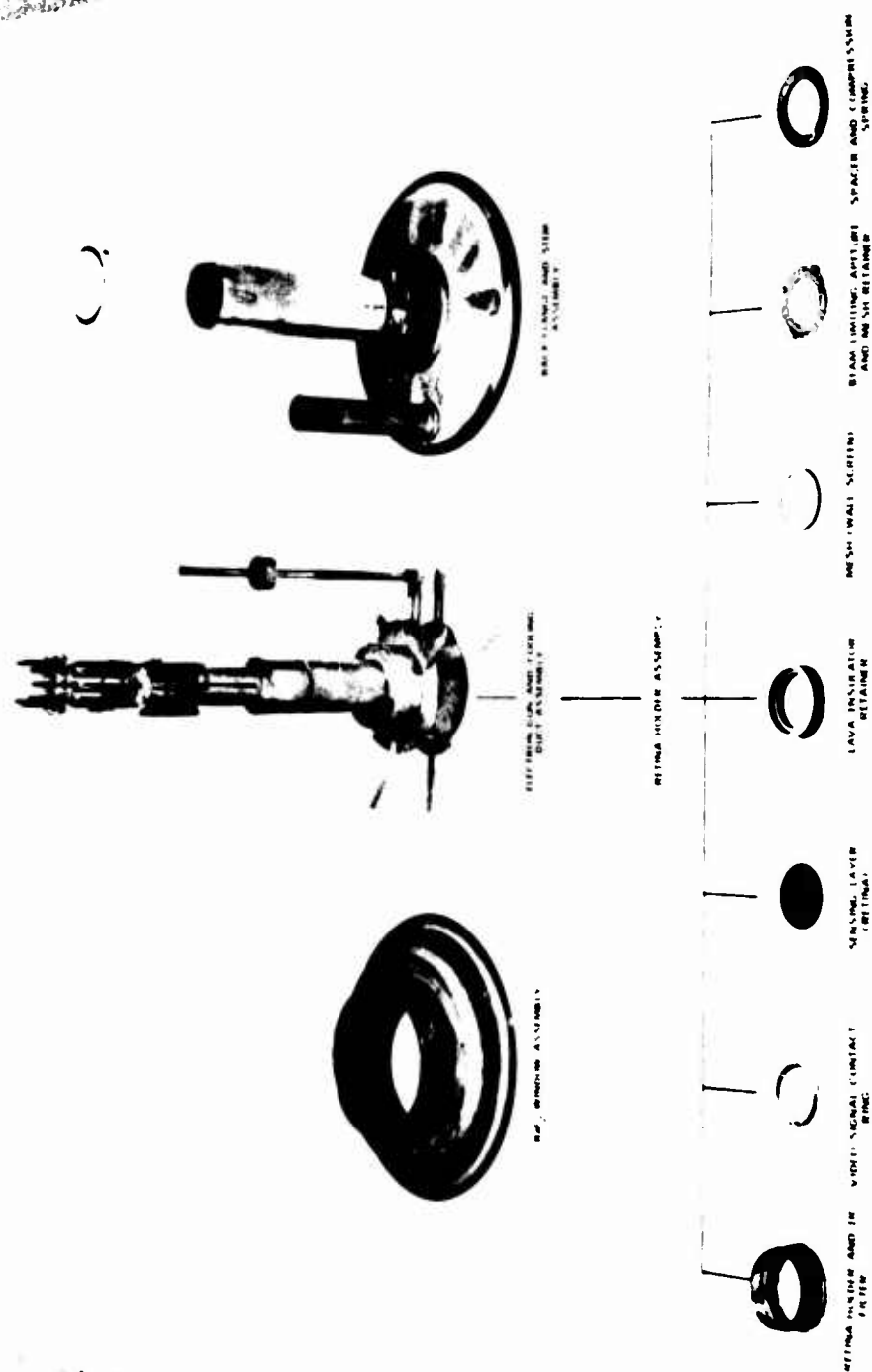
Parts for sealed-off Thermicon

Fig. 2

RM 35035
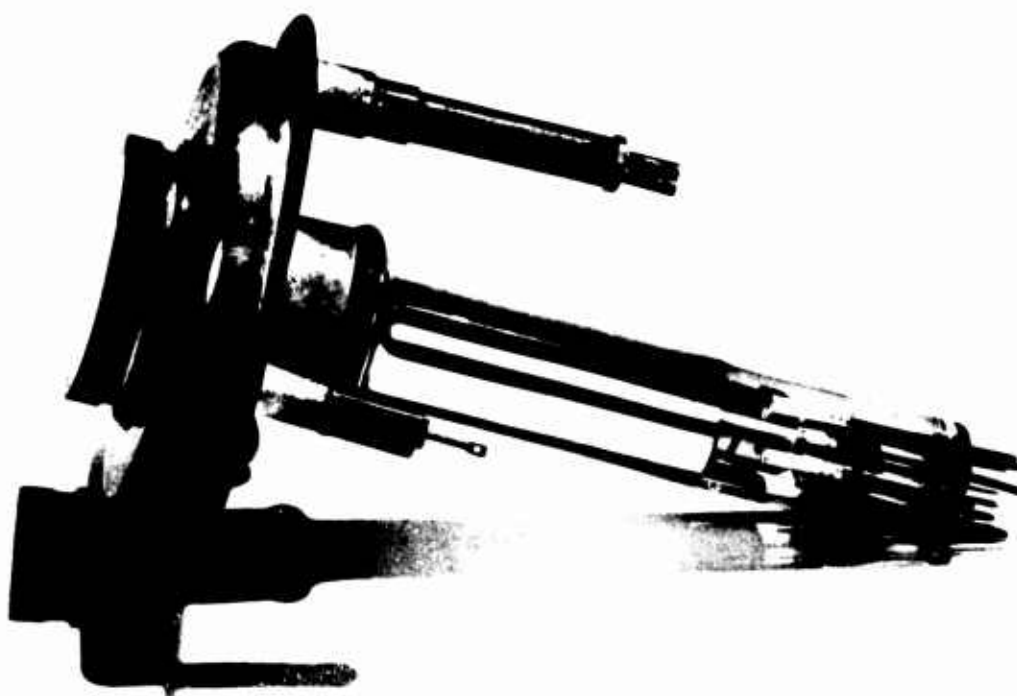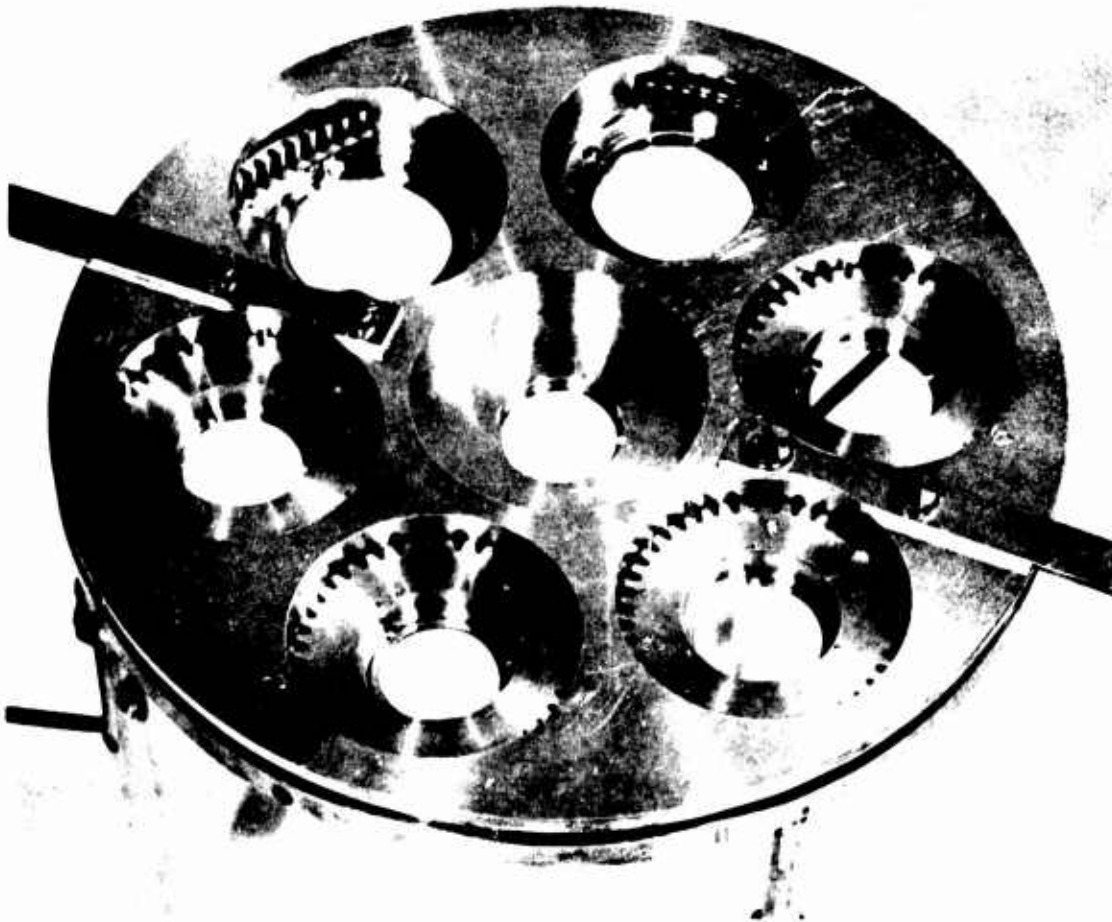
Fig. 3 —First sealed-off cooled Thermicon tube
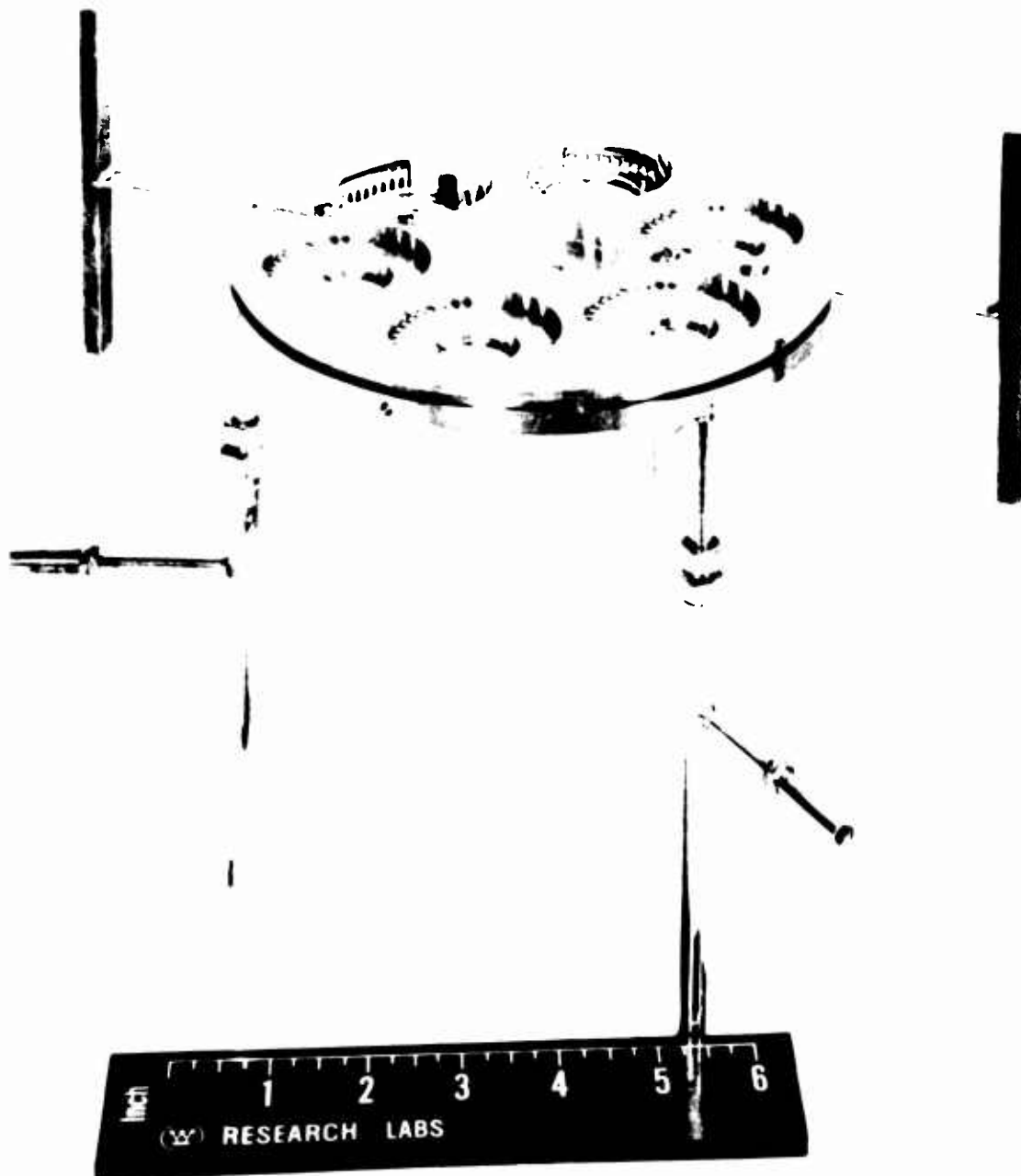
Fig. 4 - New evaporator table. The two vertical bars are soft iron and comprise part of the magnetic coupling used to rotate the table top inside the bell jar. The radial pieces extending out from the legs are for centering the table in the bell jar.
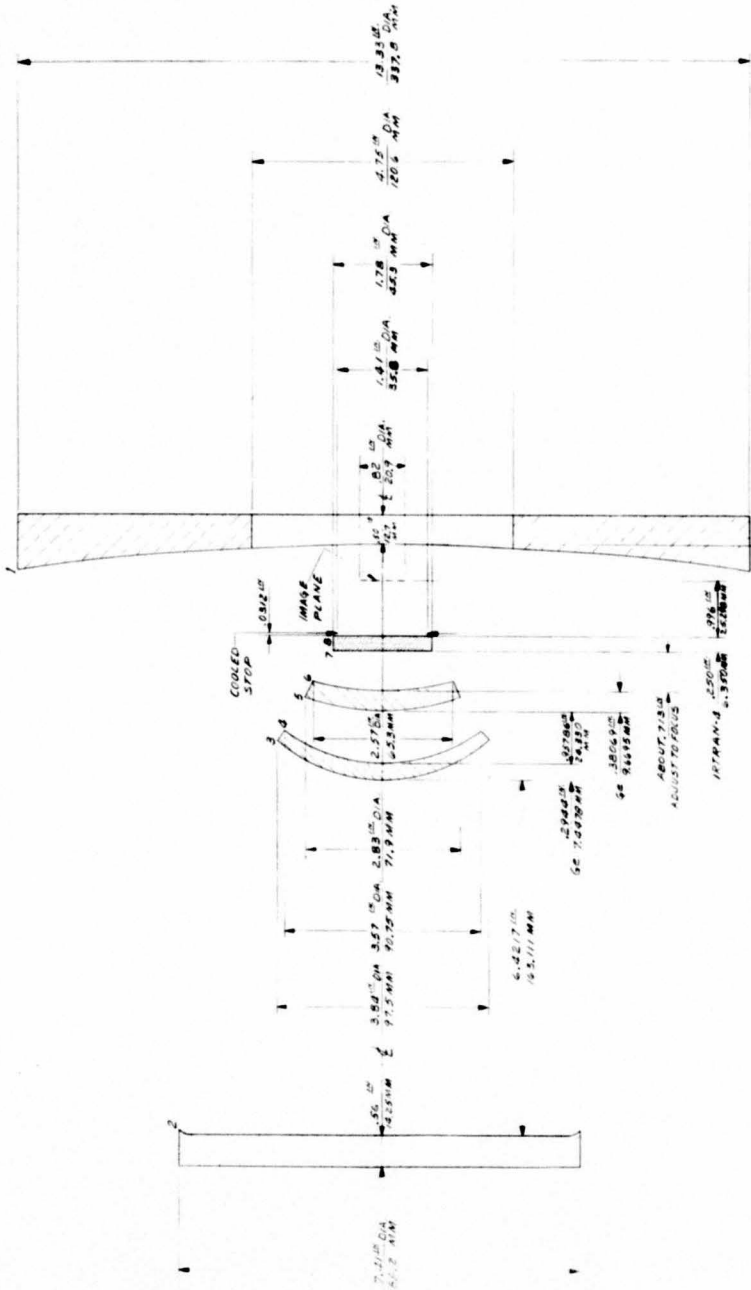
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Fig. 5 - Close-up of evaporator table top. The retina holding spur gears have been removed from positions 4 and 5 to expose the teeth of the internal ring gear near the edge of the table top.

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Fig. 6—Optical system for Thermicon
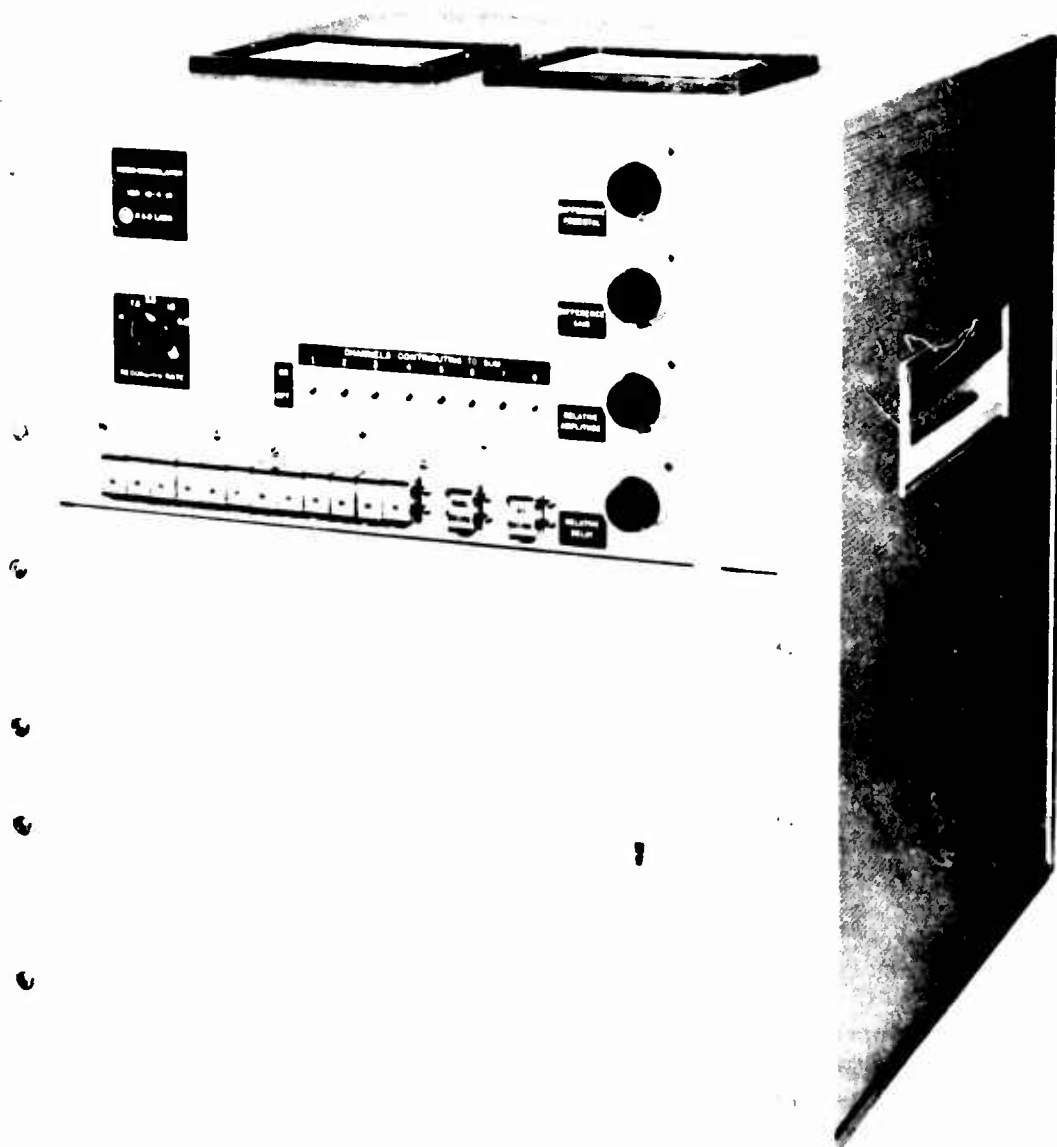
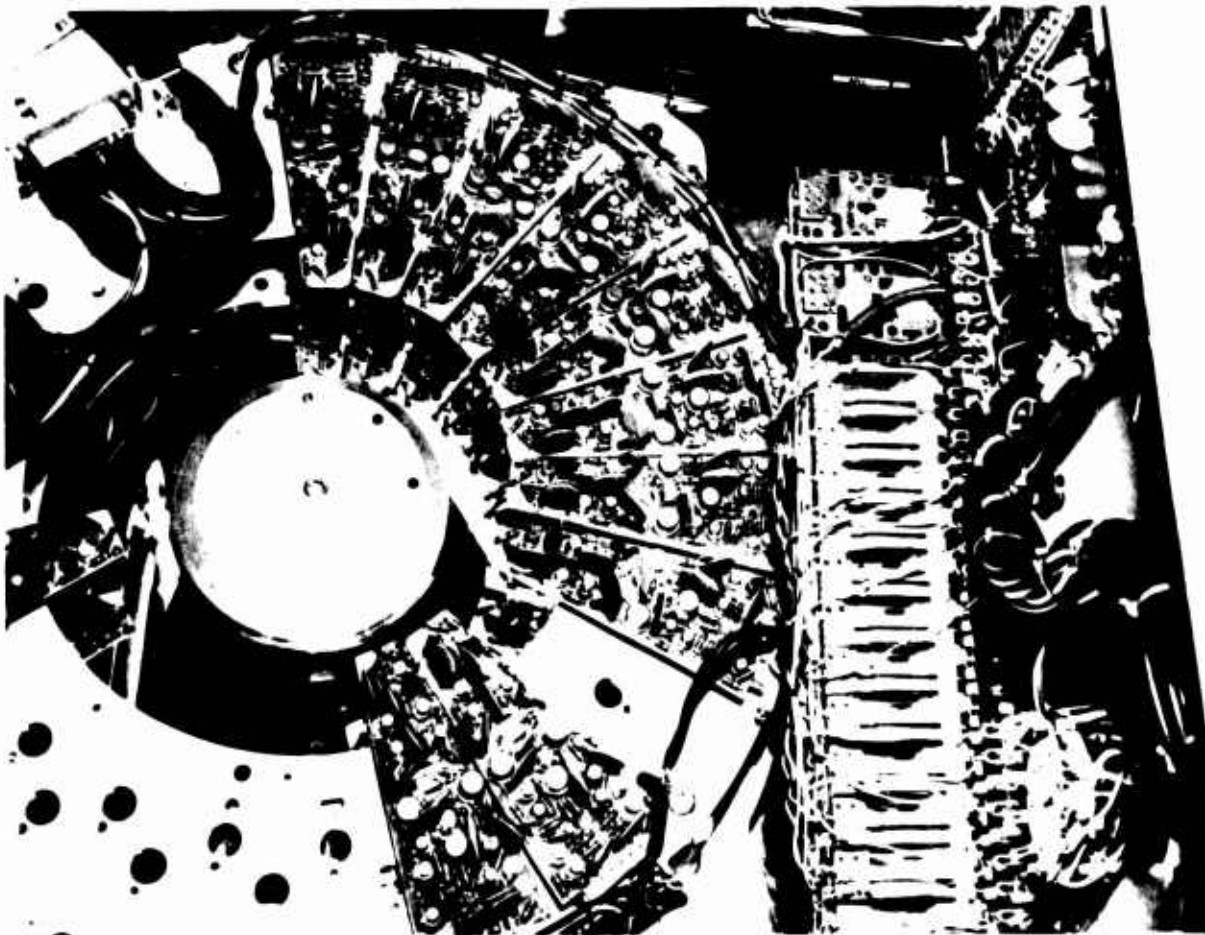Fig. 7 - External view of video correlator.

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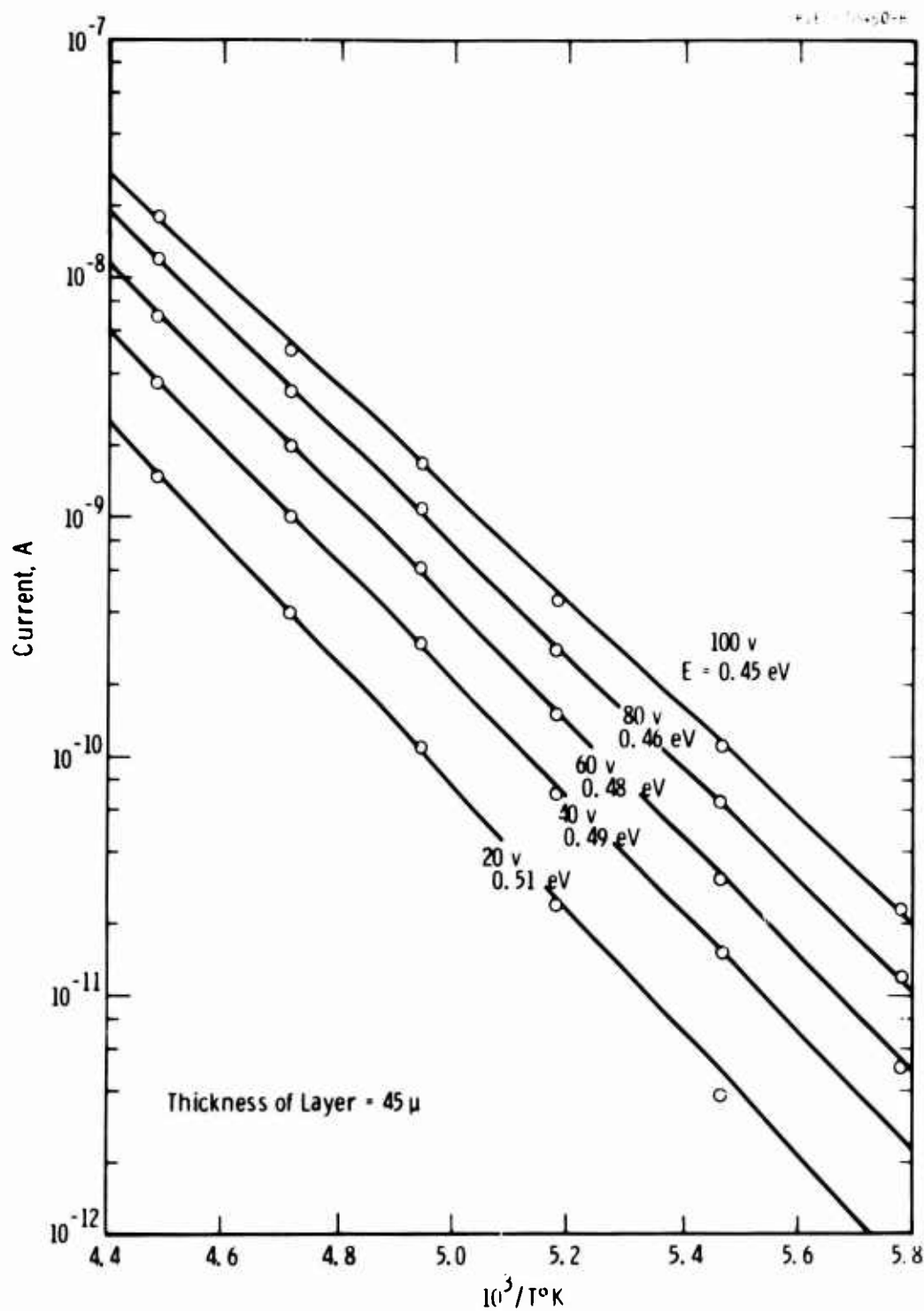
Fig. 9 — Temperature dependence of current through a smoke layer prepared from GeTe for various values of applied voltage in the range 20-100 volts. The area of the layer is 0.5 cm²
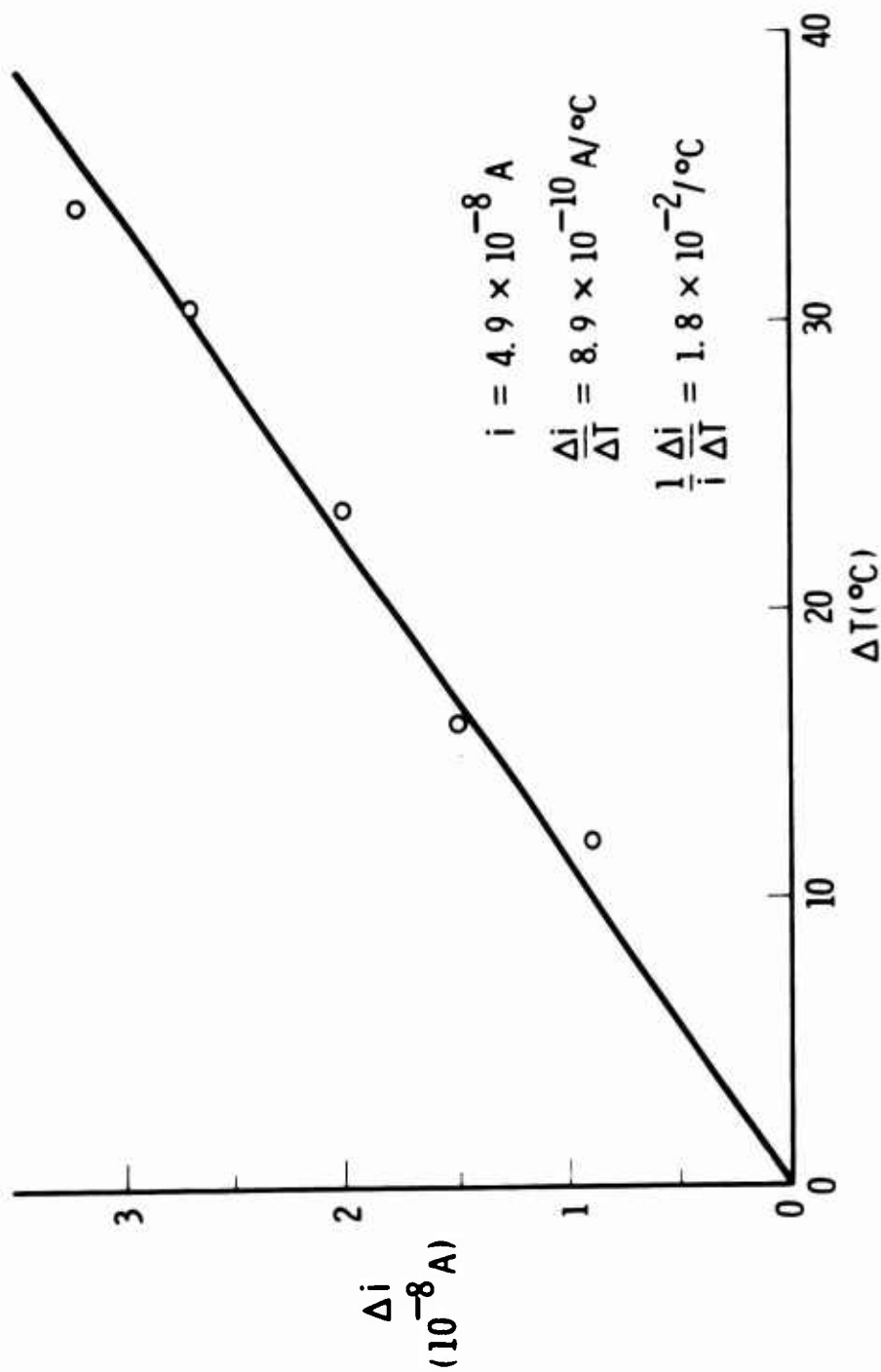
Fig. 10—Response of tube #3 with new 10' optical system. The object is a beaker of warm water ΔT °C above room temperature. The background current, corresponds to $\Delta T = 0$

$$i = 4.9 \times 10^{-8} \text{ A}$$

$$\frac{\Delta i}{\Delta T} = 8.9 \times 10^{-10} \text{ A/°C}$$

$$\frac{1}{i} \frac{\Delta i}{\Delta T} = 1.8 \times 10^{-2} / \text{°C}$$
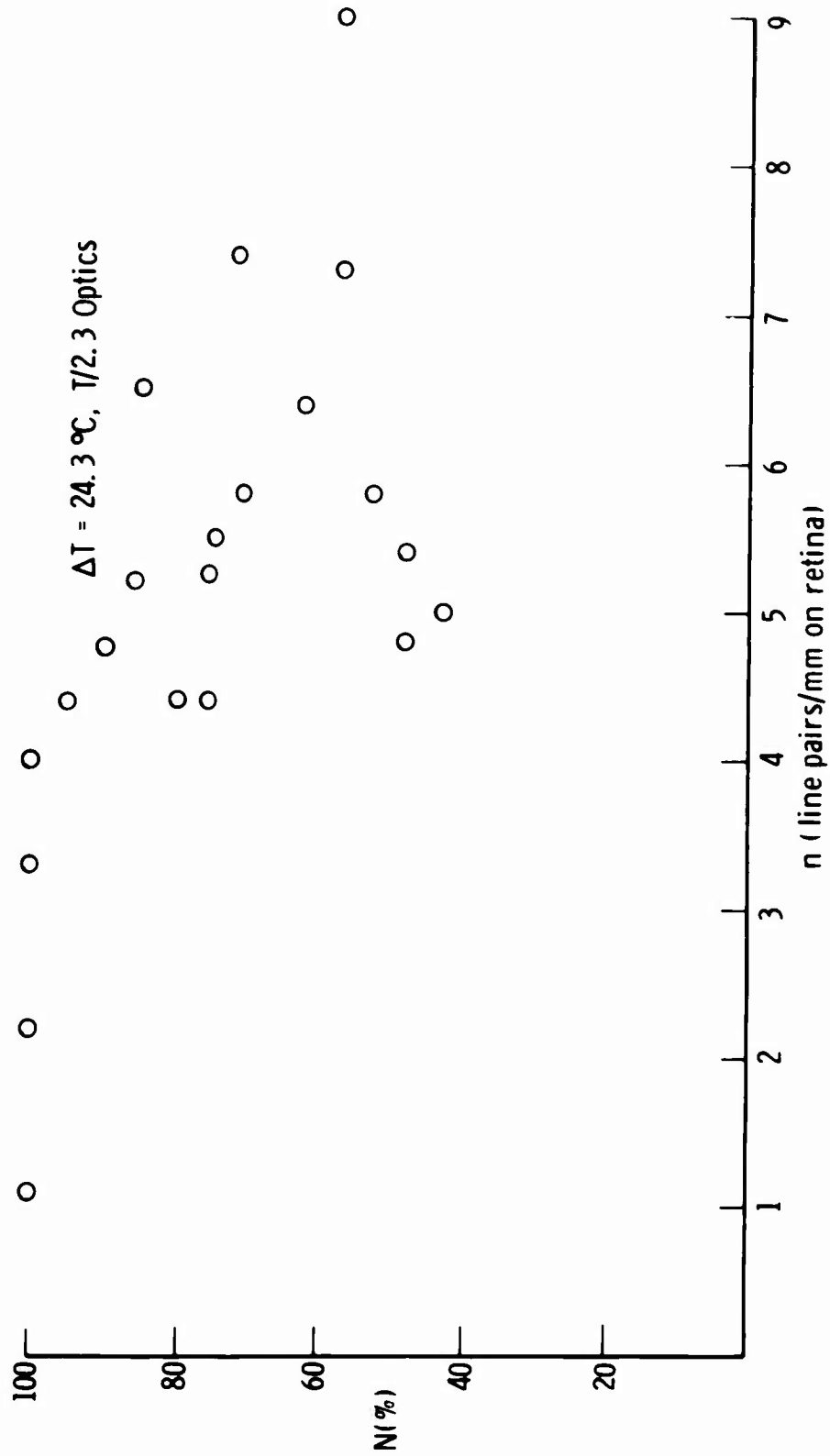
$$i = 4.9 \times 10^{-8} \text{ A, corresponds to } \Delta T = 0$$

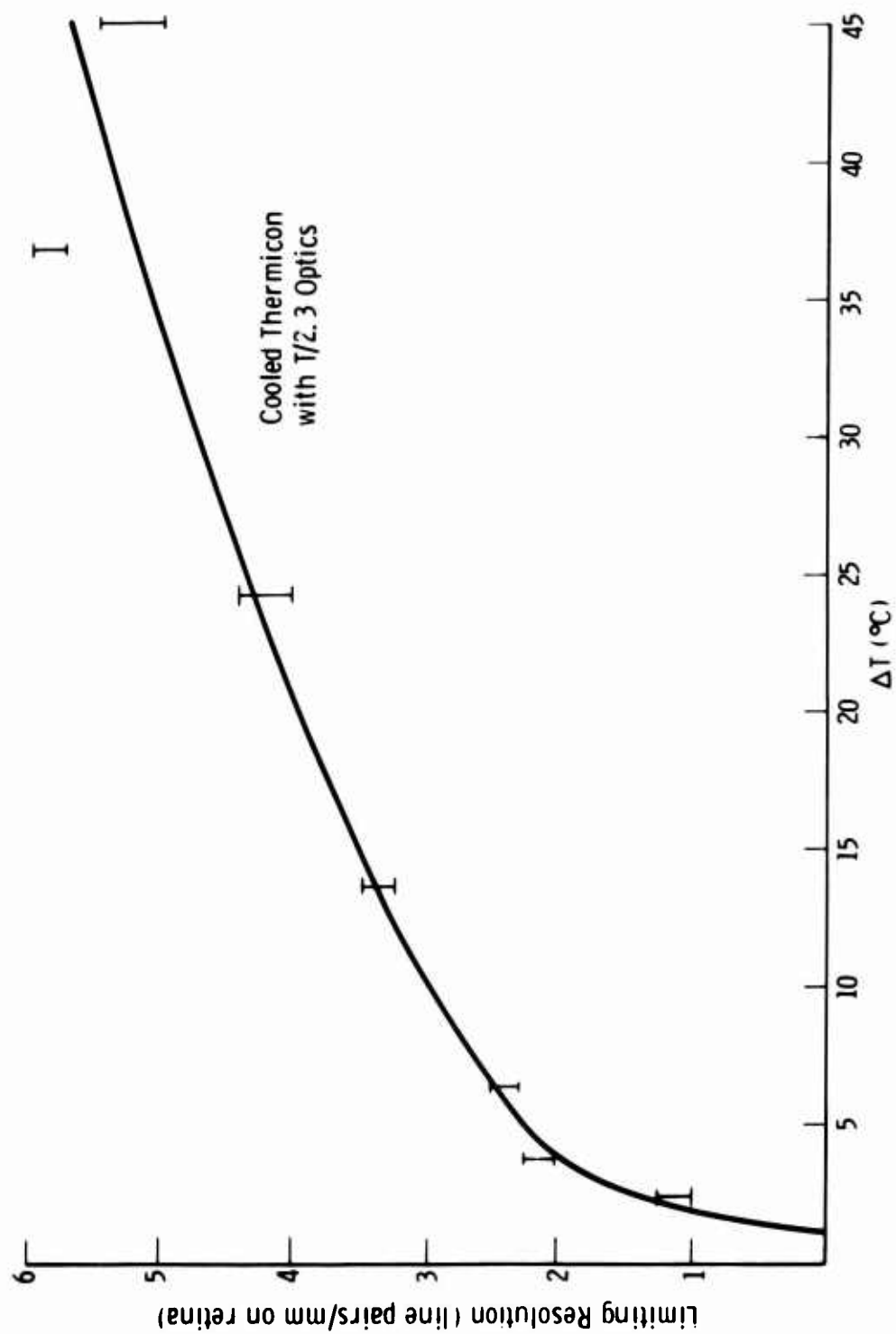Fig. 11—Percentage of correct observations as a function of line number

Fig. 12—Limiting resolution as a function of object temperature difference. Note that ΔT values scale directly with the square of the T-number (effective F-number) of the optics used
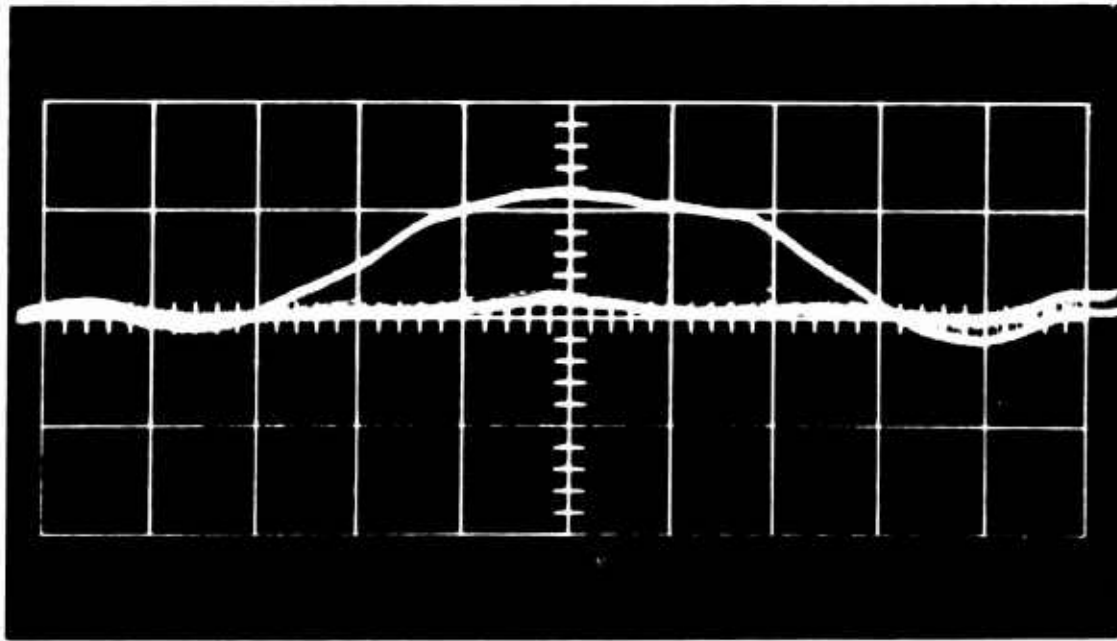
Fig. 13 — Oscillogram showing decay of cooled Thermicon output during successive frames after removal of object

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13. ABSTRACT

This report describes work on the development, design, construction and testing of the cooled Thermicon system, an infrared television system for night vision. Principles of operation and theoretical predictions of performance are given. The design and fabrication of sealed tubes and the problems of sensing layer preparation are described. A complete system, including optics, camera and cooling was built. A novel scheme for the enhancement of contrast by background subtraction was successfully implemented in a unit called a video correlator. The performance of the entire system was evaluated in outdoor night-time field tests at Ft. Belvoir, and also in a number of laboratory measurements. Two uncooled Thermicon tubes were also made and tested.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	RCLE	WT
Infrared						
Television						
Night Vision						
Camera Tubes						
Bolometer						
Contrast						
Background Subtraction						
Shading						
Optics						
Cooling						